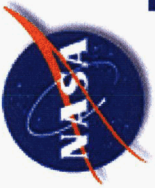


Structural Continuum Modeling of Space Shuttle External Tank Foam Insulation

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NASA Marshall Space Flight Center
Huntsville, AL

43rd Annual Technical Meeting of the Society of Engineering Science
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University Park, PA

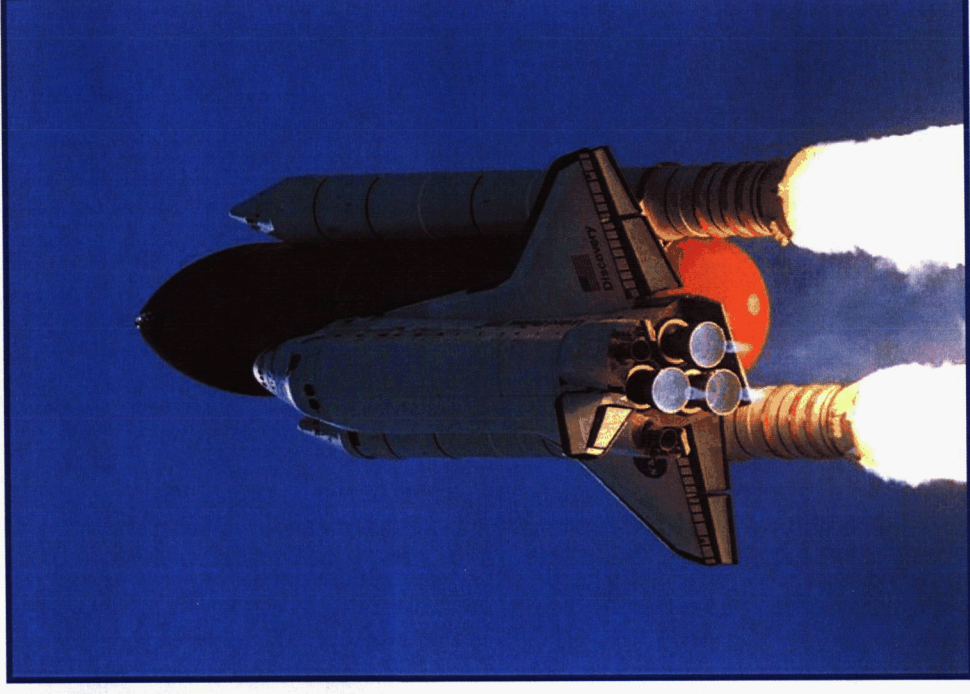
14 August 2006



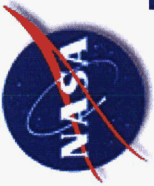
Structural Continuum Modeling of Space Shuttle External Tank Foam Insulation

Outline

- Introduction
- Foam Description
- Foam Mechanical Behavior
- Structural Modeling
- Modeling Assumptions
- Thermal Expansion
- Loading
- Ice-Frost Ramp Results
- Conclusion



STS-121 Launch



Introduction

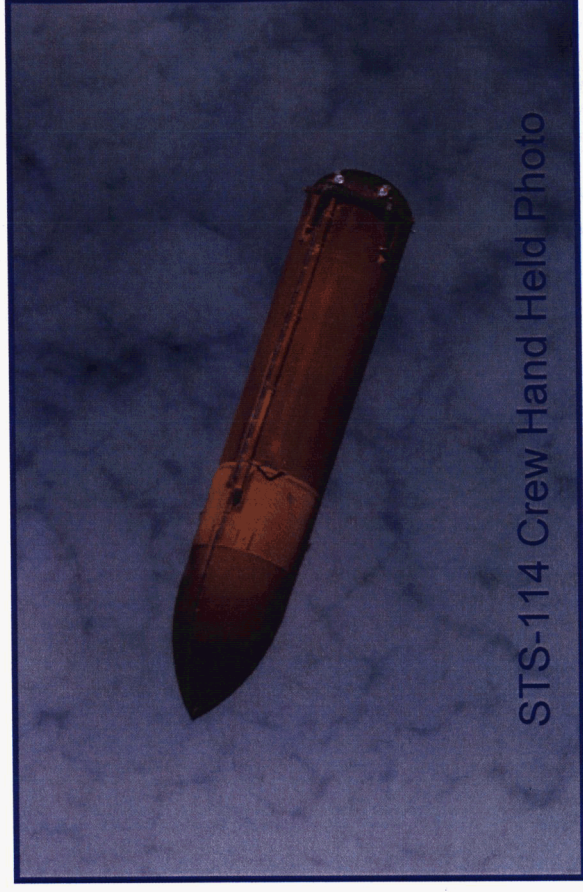
The Space Shuttle External Tank is covered primarily with closed cell foam

- Prevent ice
 - LO2 Tank -320°F, LH2 Tank -423°F
- Protect structure from ascent aerodynamic and engine plume heating
 - Up to 650°F foam surface temperature
- Delay break-up during re-entry
 - Lands over a small footprint in Indian Ocean

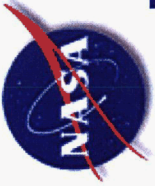
Foam required to not shed unacceptable debris during ascent environment

- Cryogenic thermal stresses
- External vacuum
- Tank pressurization strain
- Aerodynamic pressures
- Vibroacoustics

Analytical understanding of foam mechanics is required to design against structural failure



STS-114 Crew Hand Held Photo



Foam Description

External Tank foam is a rigid closed cell material of three major types

- NCFI 24-124 – Polyisocyanurate, auto-sprayed, acreage
- BX-265 – Polyurethane, manually sprayed, closeouts
- PDL-1034 – Polyurethane, poured, closeouts, repairs

The cells in all the foams are elongated to some degree in the free-rise direction.

- This results in anisotropic mechanical, strength, and fracture behavior

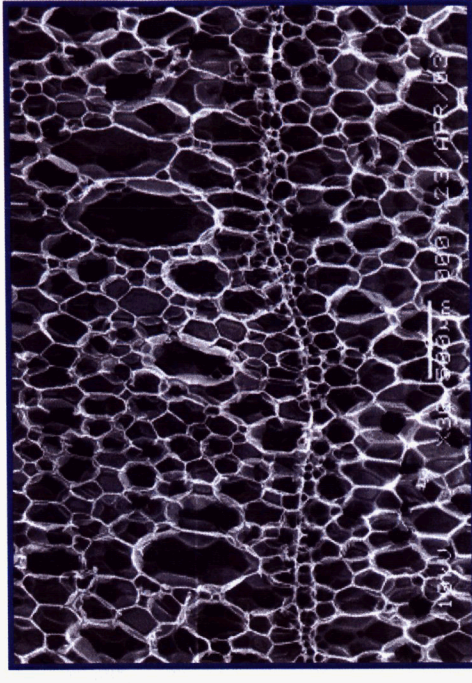
Spray-on foams have relatively dense layers, called knitlines, between each pass

- Contributes to anisotropic, non-homogeneous behavior

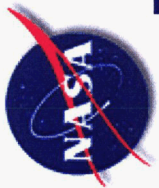
Cell sizes range from 0.007-0.016 in (175-400 μ m) and result in densities of 1.8-3.8 pcf and a relative density of approximately 0.03⁽¹⁾

The spraying and pouring of foam can leave volumes that do not fill with foam

- Resulting voids act as defects and may initiate a failure due to internal pressure



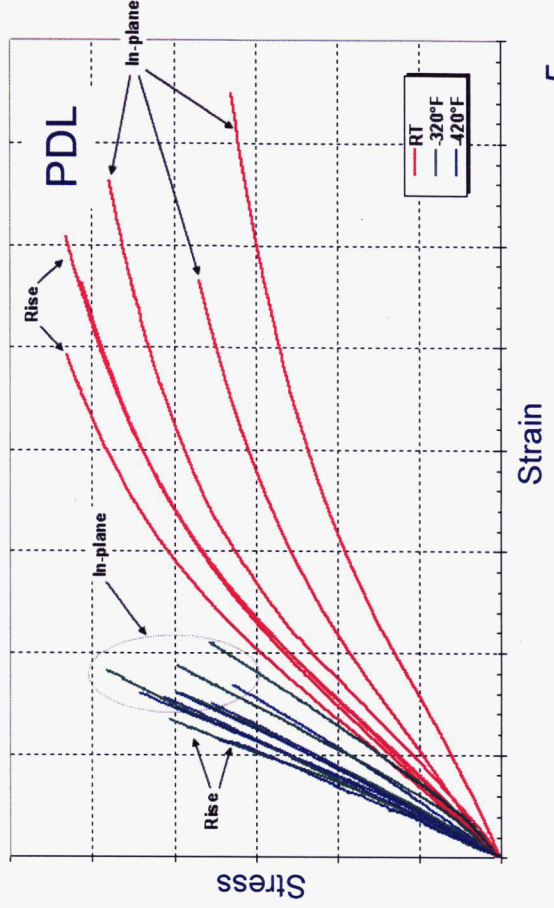
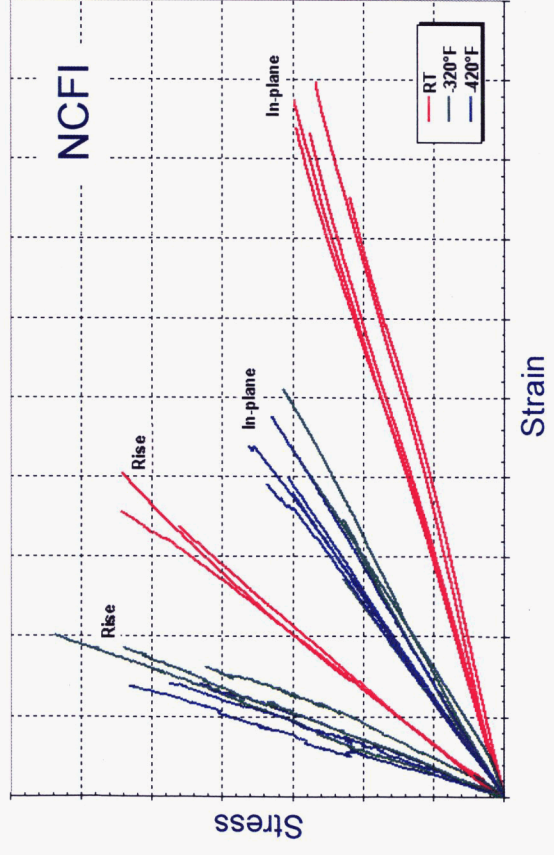
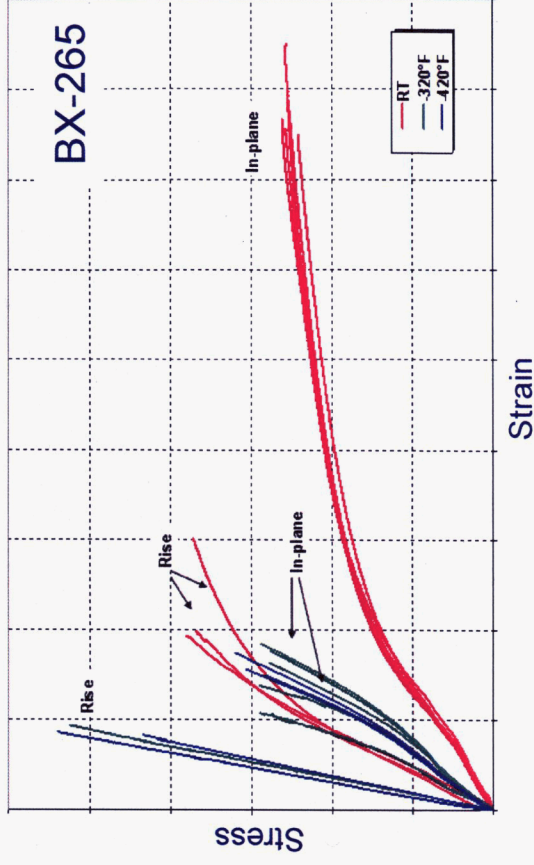
BX-265 Cell Structure

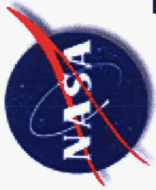


Foam Mechanical Behavior

Stress-Strain Curves

- All of these foams are linear-elastic at cryogenic temperatures
- BX and PDL exhibit non-linear response at room temperature
- NCFI is linear-elastic at all temperatures

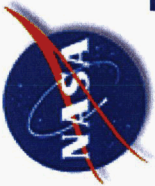




Foam Mechanical Behavior

Failure Mode

- The primary loads that drive External Tank foam loss are tensile in nature
 - In-plane tension load due to thermal mismatch and tank pressure
 - External vacuum/internal cell pressure
- Rigid polymer foam fails in a brittle fashion under tension load particularly at low temperatures
 - Brittle tensile failure is dominated by internal defects
 - Cracks initiate at internal defects and rapidly propagate
 - Creates a wide scatter in strength properties
 - Crack initiation is described by linear-elastic fracture mechanics

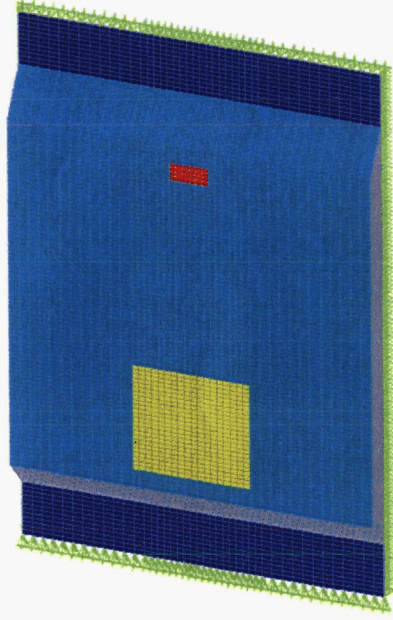


Foam Structural Modeling

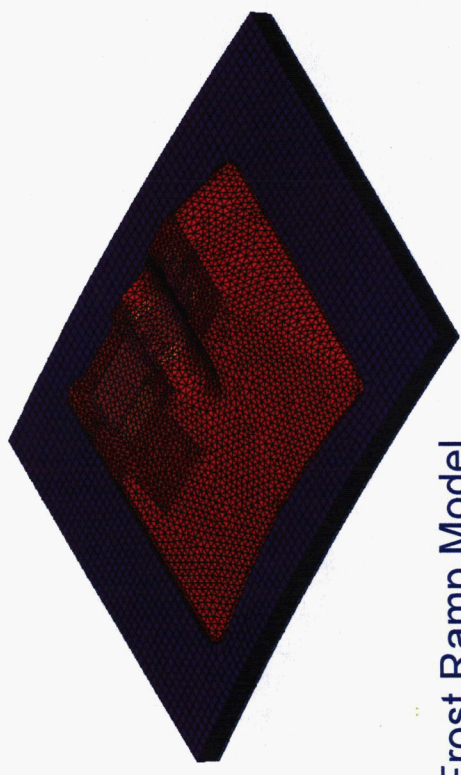
Various External Tank foam applications and test articles have been modeled to understand the response to the ascent environment

- The maturity of modeling foam is low and is not considered sufficiently accurate to predict structural integrity
- Models are used as an aide to understand the physics of the problem and to compare designs against each other
- Work at the coupon and subcomponent level continues to develop foam material models

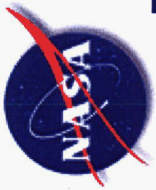
The models used to date are continuum based using solid finite elements and bulk foam properties to simulate part behavior



LO2 Wide Panel Test Model



LO2 Ice-Frost Ramp Model



Modeling Assumptions

Several simplifying assumptions are made in the foam models

- **Linear-elastic material model**

- Assumes non-linear response not significant for foam on a cryogenic substrate
 - Peak stress occurs near cold substrate
 - Warm temperatures are near the surface where stress is low or compressive

- **Transversely isotropic behavior**

- Same properties assumed for directions transverse to rise direction

- **Homogeneous**

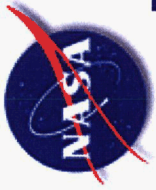
- Irregular nature of cell structure and knittines ignored
- Uses bulk mechanical properties from coupon tests

- **Internal cell pressure follows ideal gas law**

- Neglects cell expansion

- **Elastic modulus set to near zero at elevated temperatures**

- Simulates softening that occurs at temperatures in the 200-400°F range



Thermal Expansion

- Thermal expansion of foam is due to the expansion of the solid polymer and due to the effect of the increase in internal cell pressure on the cell structure
- The internal cell pressure is modeled by applying a pressure to every face of every element based upon the local temperature
 - Pressure is assumed to vary according to the ideal gas law
 - Pressure assumed to be 1 atm at room temperature
- The coefficient of thermal expansion included in the model only needs to account for the solid polymer expansion
- Thermal expansion testing results include the expansion due to both effects
 - Must isolate the expansion due to each effect
- Thermal expansion testing was performed in both ambient and vacuum conditions
 - Allows the solid polymer expansion to be estimated



Thermal Expansion

Assuming the internal cell gas is at 1 atm at room temperature and the pressure follows the ideal gas law (neglecting any volume change) then the solid polymer thermal expansion can be estimated from the thermal expansion data taken at ambient and vacuum conditions as:

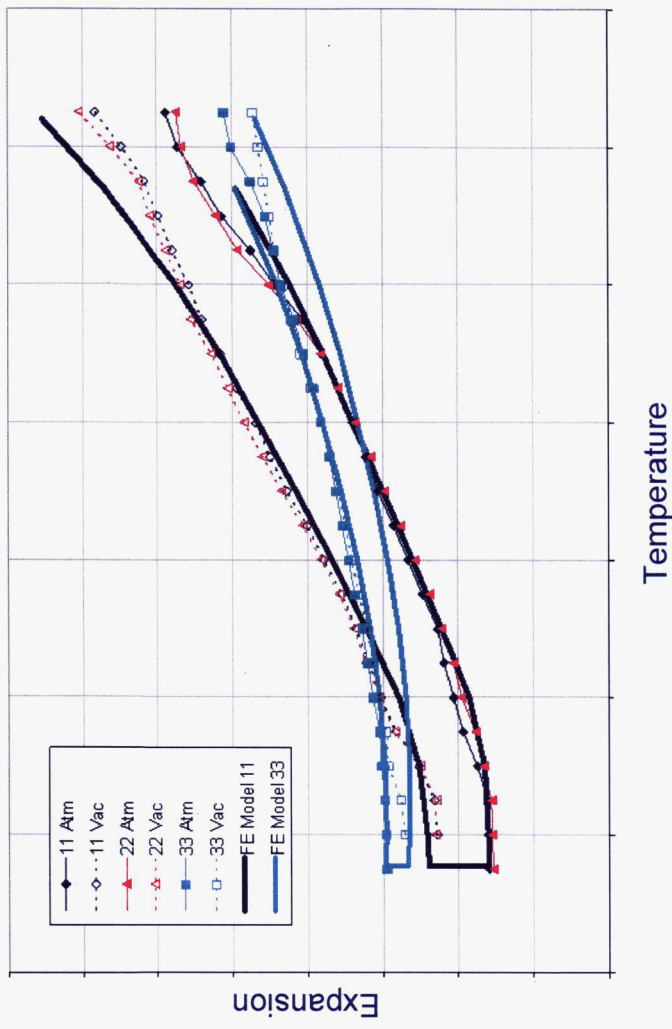
$$\alpha_x = \frac{\epsilon_x}{T - T_o} - \frac{p_{ext}}{T_o} \cdot \frac{\epsilon_x^V - \epsilon_x^A}{p_{ext} - p_{ext}^V}$$

$$\alpha_y = \frac{\epsilon_y}{T - T_o} - \frac{p_{ext}}{T_o} \cdot \frac{\epsilon_y^V - \epsilon_y^A}{p_{ext} - p_{ext}^V}$$

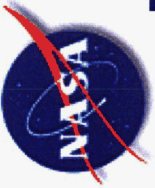
$$\alpha_z = \frac{\epsilon_z}{T - T_o} - \frac{p_{ext}}{T_o} \cdot \frac{\epsilon_z^V - \epsilon_z^A}{p_{ext} - p_{ext}^V}$$

The results give similar values for α in all directions and between all three foam types

$$\alpha \approx 3.0\text{-}4.0 \times 10^{-5} \text{ in/in/}^\circ\text{F}$$

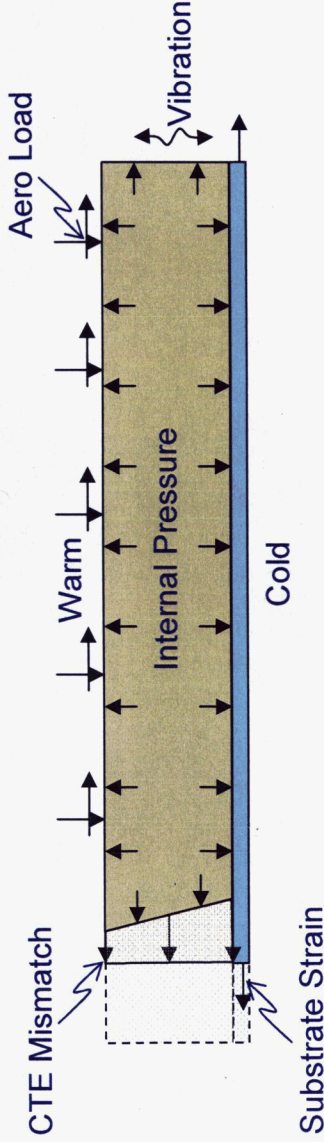


Model Comparison with Data

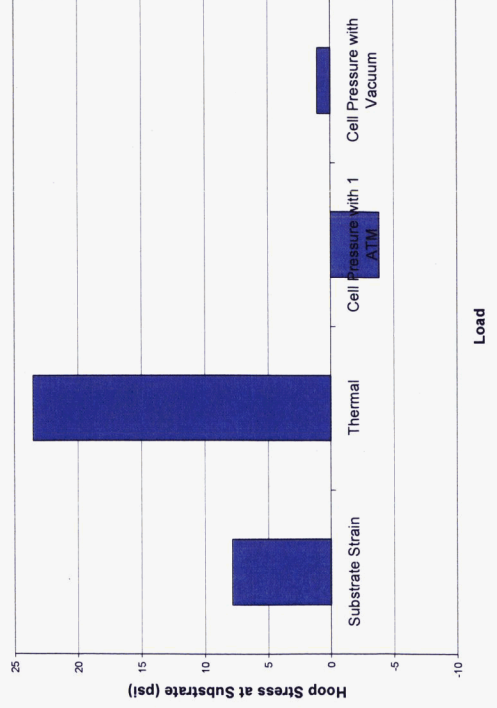


Loading

- The loads seen by the tank foam are shown below

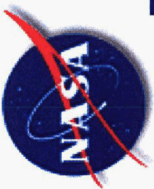


- The vast majority of the external tank foam is 1-2" thick relatively flat sheet
- Protuberances experience greater aerodynamic loads
- Thicker foam, including foam over foam, has a greater portion at cold temperatures due to the insulating effect



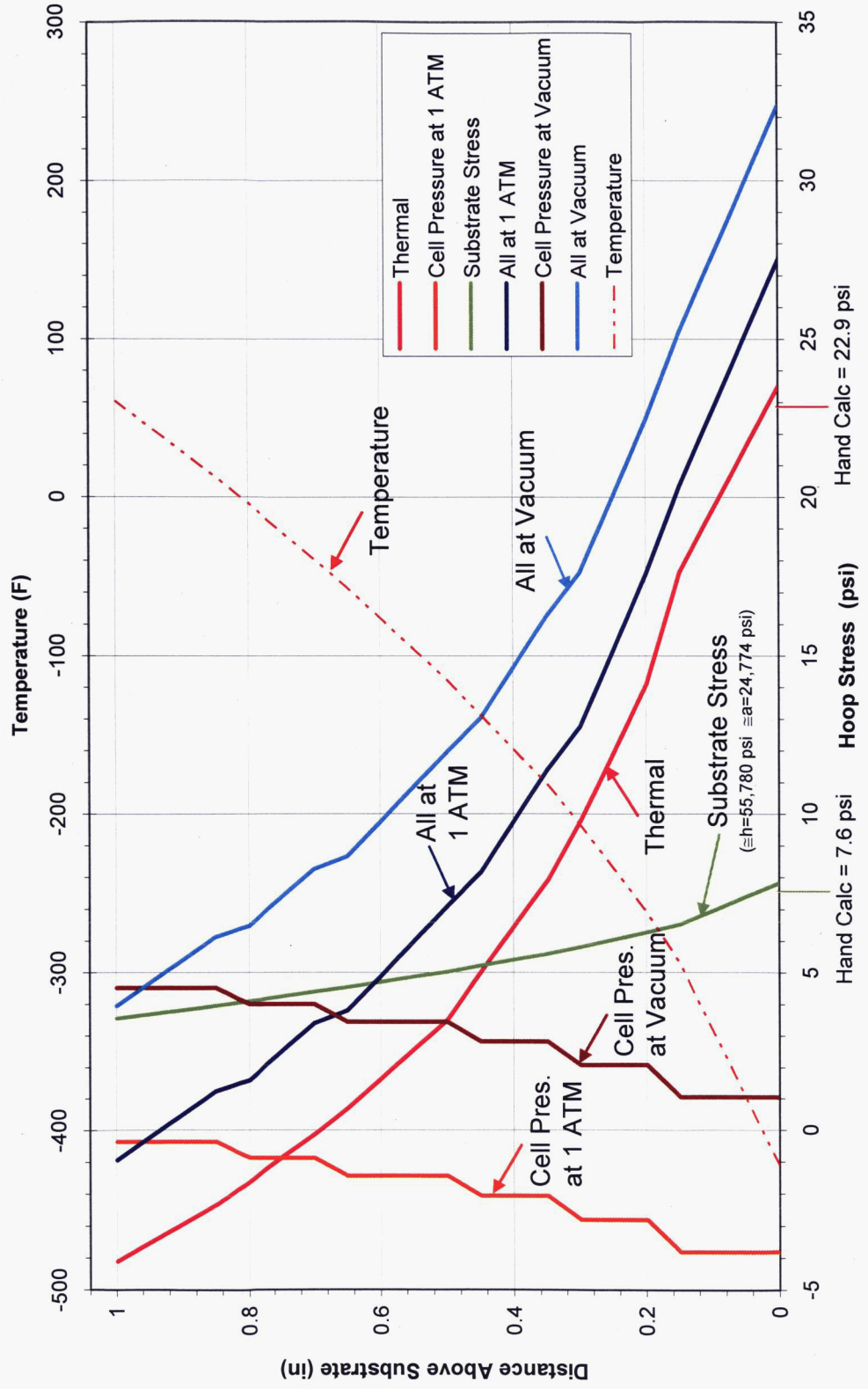
Pre-Launch Hoop Stress at Substrate

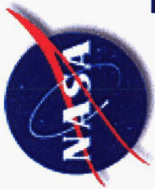
- Thermal stress is primary load
- Aero and vibration load stresses are on the order of 1-2 psi



Critical Loads

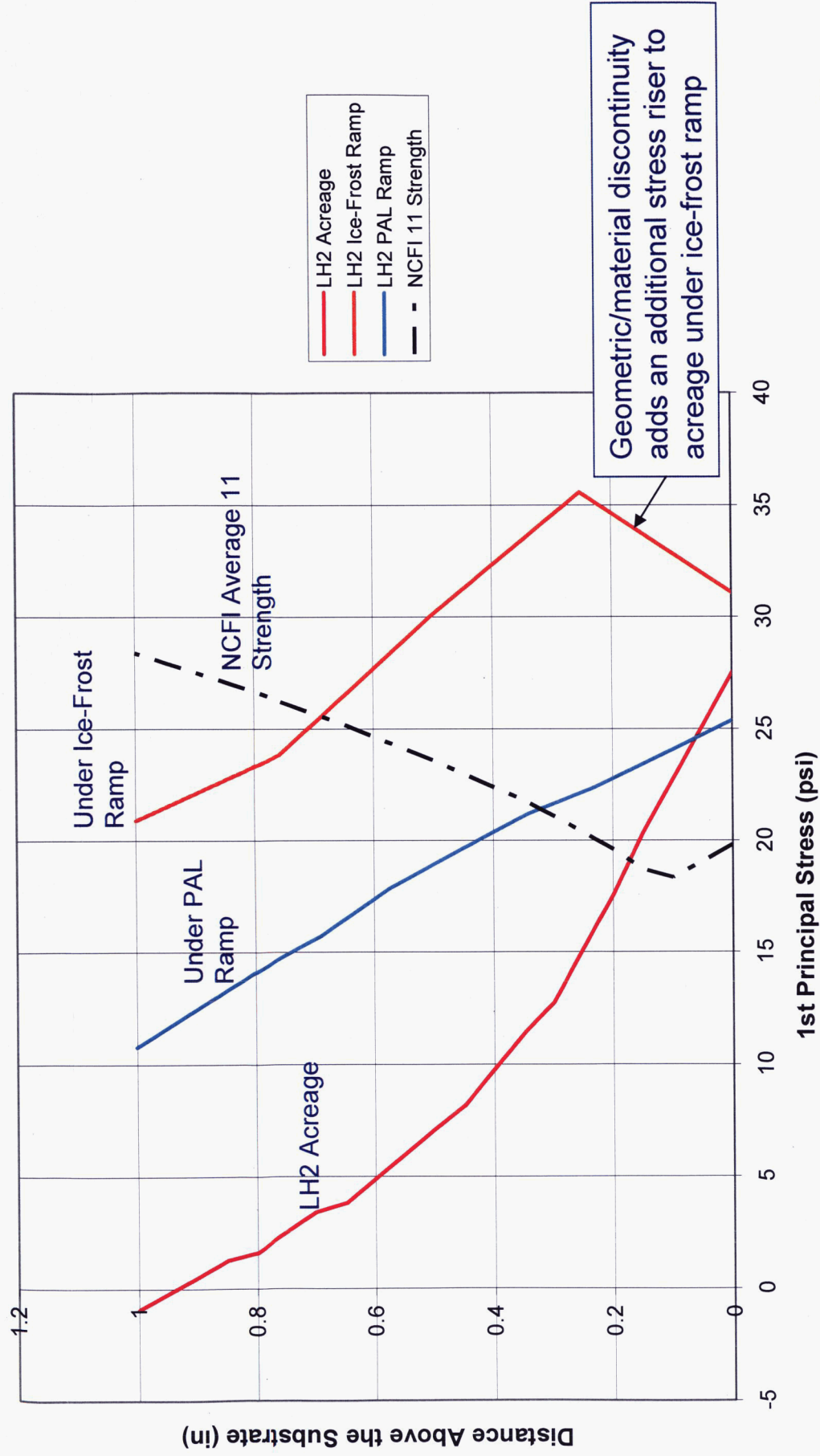
LH2 Tank Acreage Through Thickness Stress

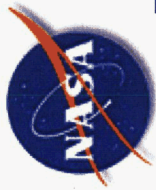




Foam over Foam Effects

Foam over acreage foam increases the through thickness stress

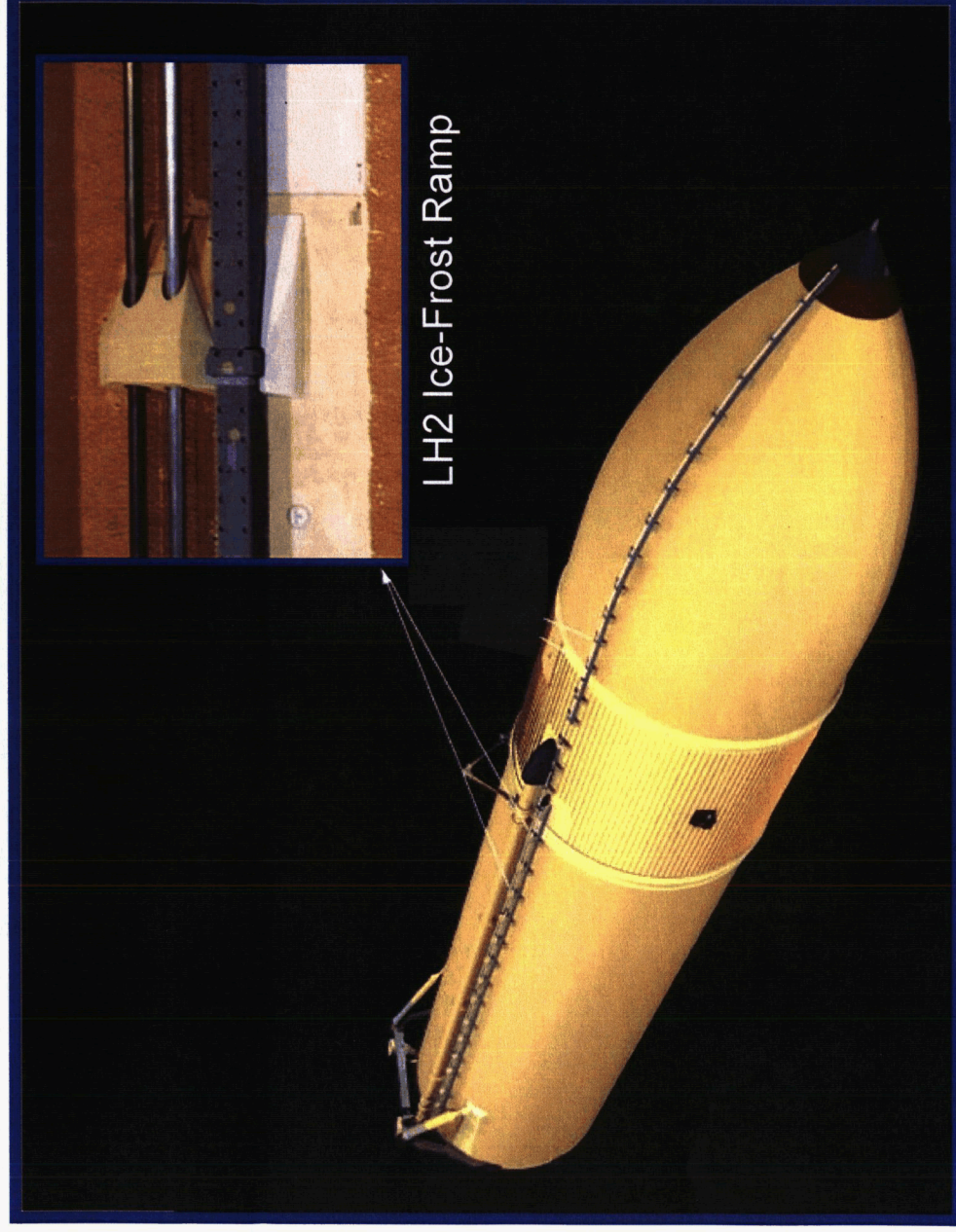


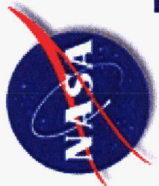


LH2 Ice-Frost Ramps

Ice-frost ramps are thick foam over foam applications running the entire length of the external tank

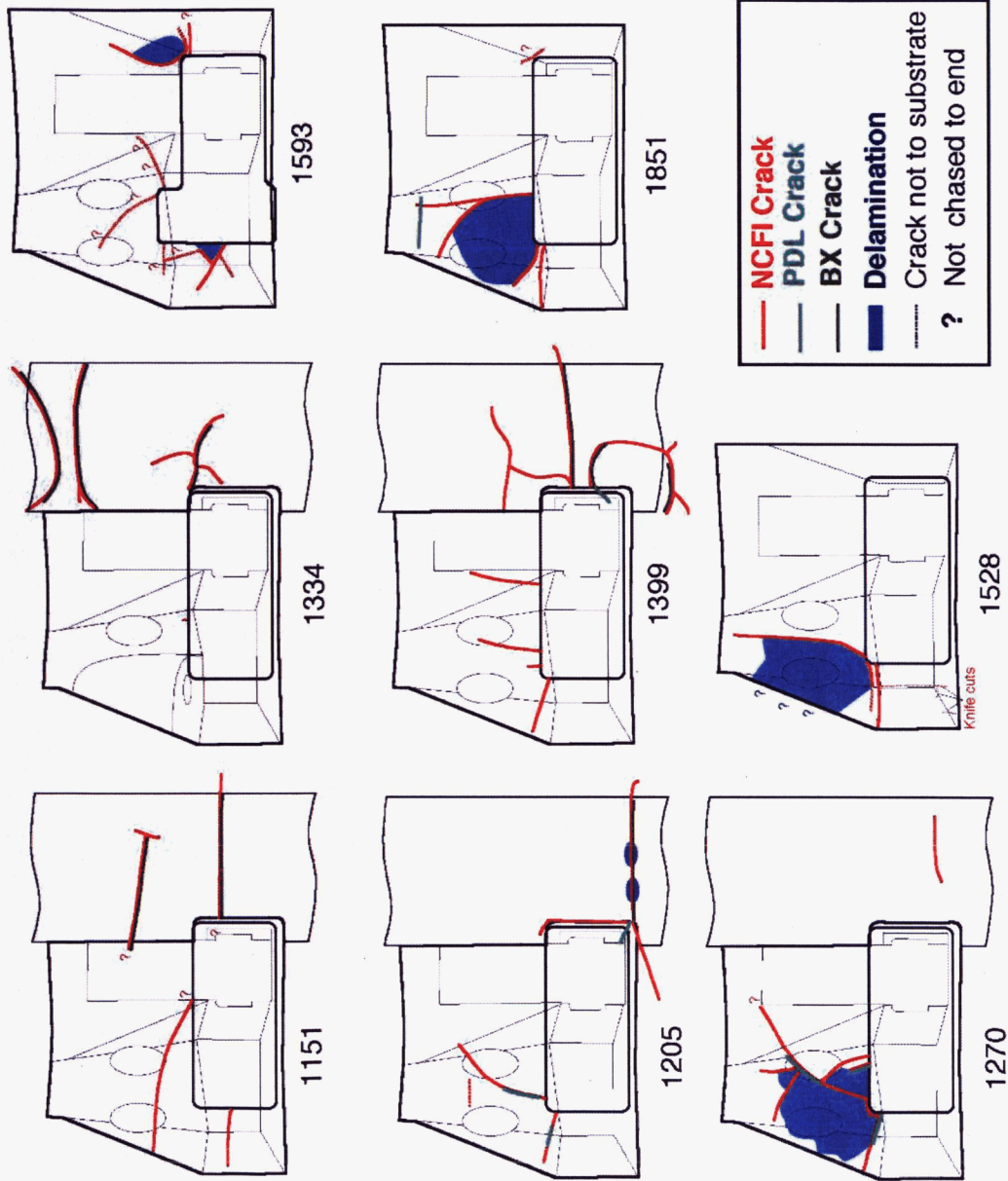
- Insulate and direct flow around structural brackets

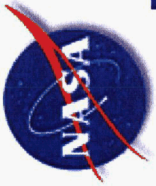




ET-120 LH2 Ice-Frost Ramp Dissection Results

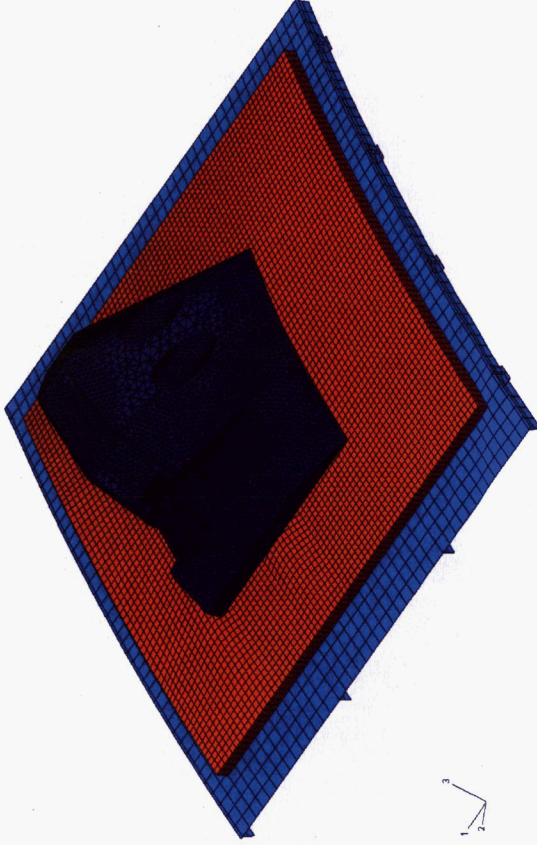
Dissection results show multiple cracks and delaminations under the thick portion of the ice-frost ramp forward and inboard of the bracket



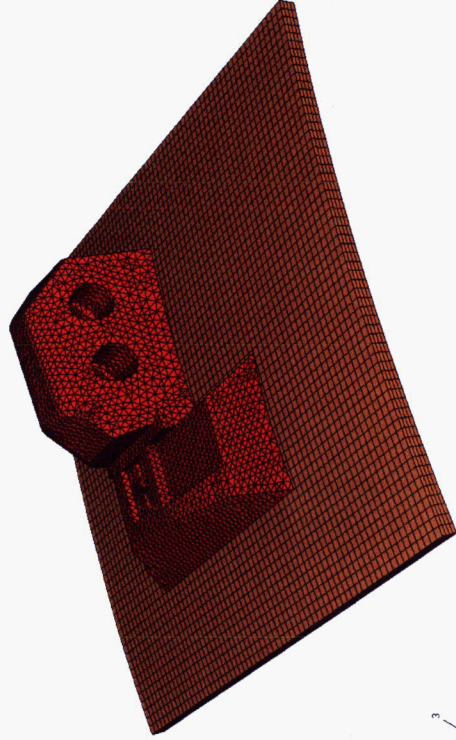


Ice-Frost Ramp Models

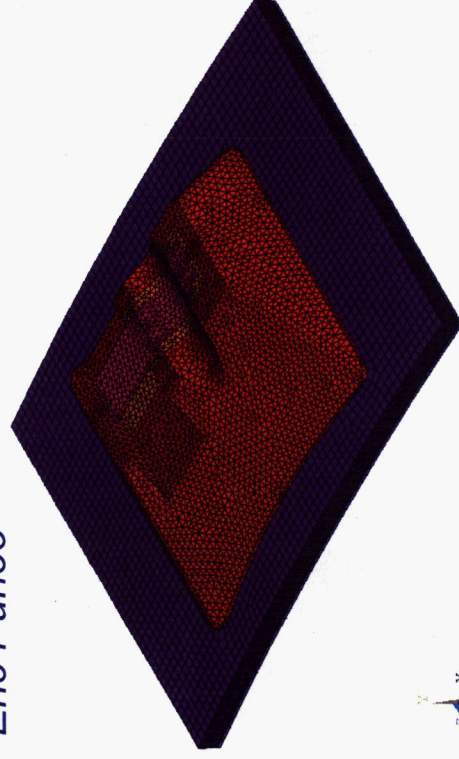
Finite element models of three ice-frost ramp designs were used to assess the relative stress levels in each one



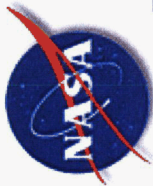
Current LH2 Ice-Frost Ramp Model
Eric Purlee



Redesign LH2 Ice-Frost Ramp Model
Sam Ayala

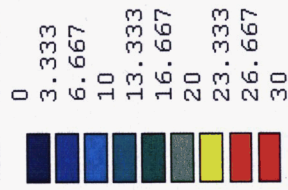


LO2 Ice-Frost Ramp Model
Phil Shaw



LH2 vs. LO2 Ice-Frost Ramp

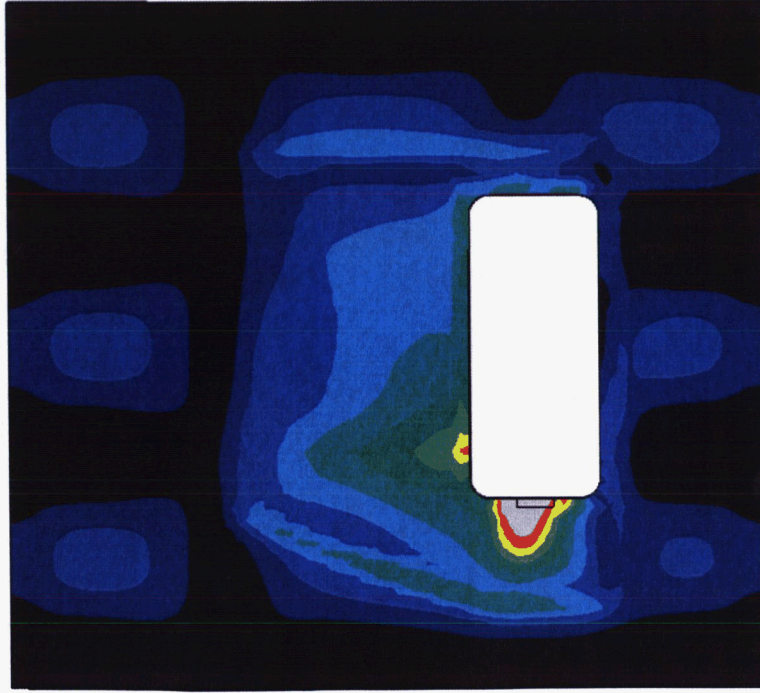
Top Surface of NCFI (Pre-Launch)
Max. Principal Stress (psi)



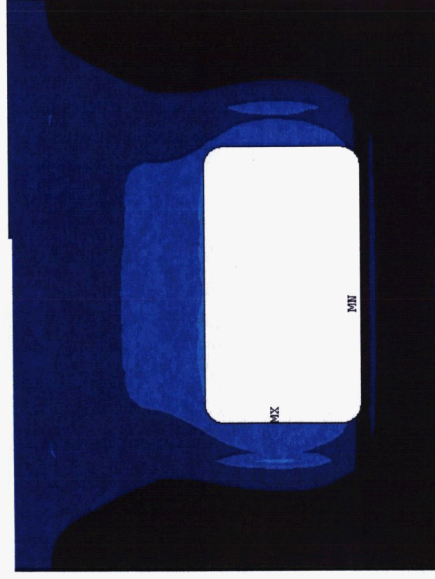
Forward



Approximately
to Same Scale

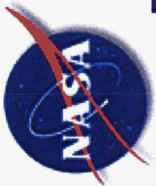


LH2 Tank IFR (pre-launch)



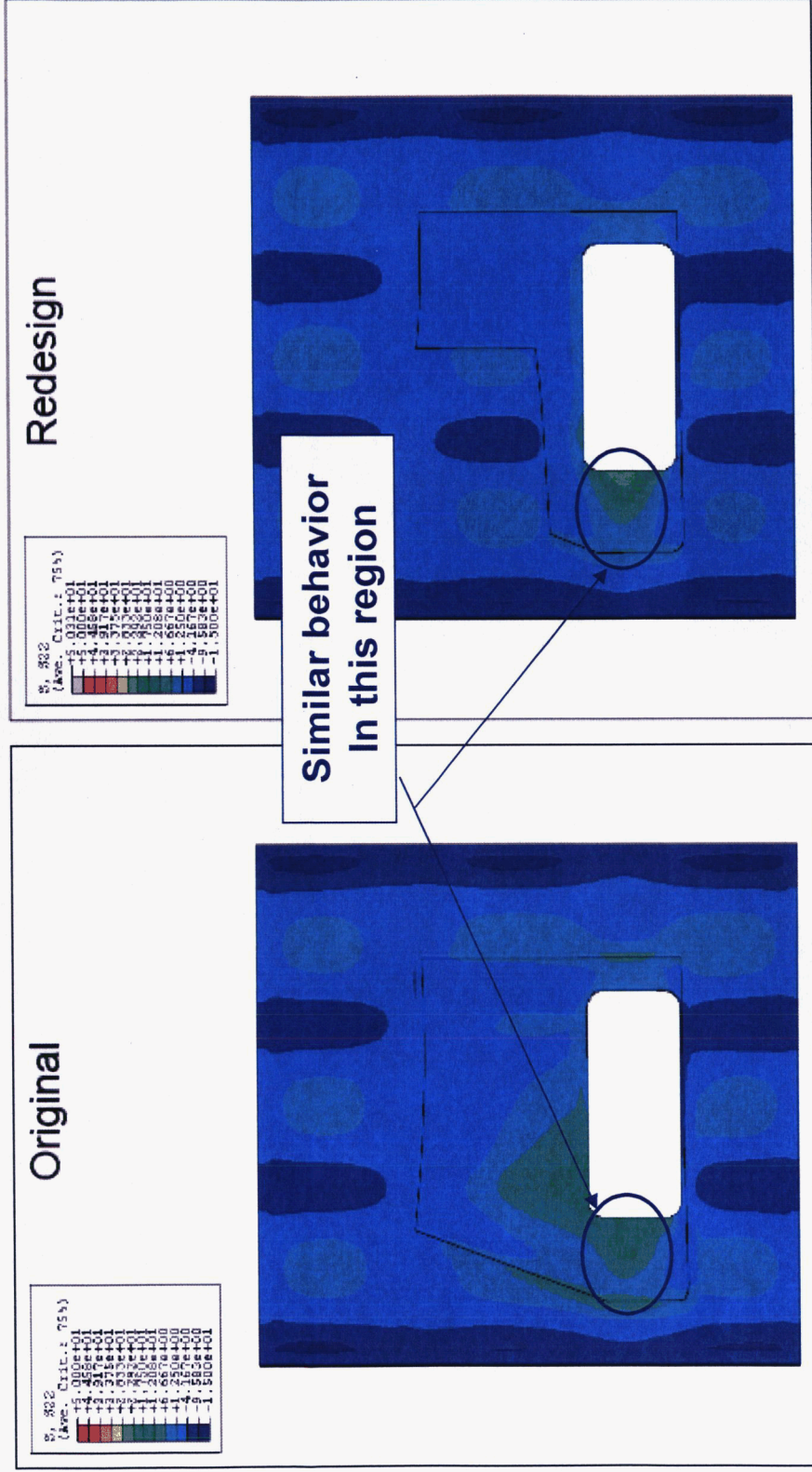
LOX Tank IFR (pre-launch)

No cracks noted in LO2 ice-frost ramps dissected on ET-120

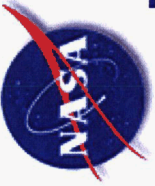


LH2 Ice-Frost Ramp

Top Surface of NCFI (Pre-Launch)
Hoop Stress (psi)



Redesign eliminates large region of thick foam over NCFI and associated region of high stress



Conclusion

- The linear elastic nature of the external tank foam insulation in cryogenic applications lends itself to a simple model
- Models are valuable for comparing different designs and effects of different loadings
- Model results can not be compared with foam strengths due to lack of understanding of foam behavior at this time
 - Few orthotropic properties available
 - Multi-axial stress state effect on foam strength unknown
- Thick foam applications significantly drive up the stress in the foam near the substrate
- The LO2 ice-frost ramps and the redesigned LH2 ice-frost ramp have significantly reduced stress levels compared to the current LH2 ice-frost ramp